Neutrino Properties from Measurements using Astrophysical and Terrestrial Sources

A.B. McDonald

Physics Department, Queen's University, Kingston, Ontario, Canada, K7L3N6

Abstract.   The current knowledge of neutrino properties has been derived from measurements performed with both astrophysical and terrestrial sources. Observations of neutrino flavor change have been made with neutrinos generated in the solar core, through cosmic ray interactions in the atmosphere and in nuclear reactors. A summary is presented of the current knowledge of neutrino properties and a description is provided for future measurements that could provide more complete information on neutrino properties.

1.   Introduction

The neutrino has been very elusive in revealing its basic properties to experimenters. However, it provides a very attractive means for the study of many astrophysical objects such as the Sun, supernovae and other astrophysical sources producing high energy particles. The study of neutrinos from these sources can provide information on both the sources and on basic properties of neutrinos themselves. This paper will discuss the current state of information on neutrino properties, in several cases obtained from measurements with astrophysical sources. Future neutrino measurements will be described for astrophysical or terrestrial sources. Other papers in this session will discuss measurements of astrophysical sources using this basic information on neutrino properties.

2.   Neutrino Properties

2.1.   Number of neutrino types

The number of active neutrino types has been restricted for many years by studies of Big Bang Nucleosynthesis (for a summary see Hagiwara et al, 2002) to be less than about 4, but considerably more accuracy has been obtained through measurements of the width of the Z^0 resonance that set a number of 2.994 ± 0.012. Neutrino flavor change measurements show no evidence for sterile neutrinos.

2.2.   Neutrino Flavor Change

Several measurements have indicated that neutrino flavor change occurs; the most favored explanation for the mechanism is neutrino oscillations among finite

mass eigenstates. The neutrino flavor fields ν_ℓ can be expressed as superpositions of the components ν_k of the fields of neutrinos with definite masses m_k via U, the 3 x 3 unitary Maki-Nakagawa-Sakata-Pontecorvo (MNSP) mixing matrix (Maki et al, 1962, Gribov and Pontecorvo, 1969).

The MNSP matrix can be parameterized in terms of 3 Euler angle rotations and a CP-violating phase δ_{CP},

$$\mathbf{U} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$.

When the neutrinos travel in a vacuum or low density region and two mass eigenstates dominate the process, the following probability is predicted for subsequent detection of a given neutrino type after it has traveled for a distance L in vacuum: $P = 1 - 1/2 \sin^2(2\theta_{ij})(1 - \cos(2.54\Delta m^2 L/E))$, where Δm^2 is the difference between the two relevant mass eigenstates in eV^2, L is the source-detector distance in meters, E is the neutrino energy in MeV and θ_{ij} is defined above. When the neutrinos pass through regions of high electron density, the difference in the interaction of electron neutrinos and other neutrinos due to the charged current interaction can add extra terms to the MNSP matrix, resulting in a change to the effective masses and coupling constants. This is referred to as the MSW effect (Mikeyev and Smirnov, 1985, Wolfenstein, 1978) and can be used to determine the sign of the mass difference of the two dominant neutrinos involved in the oscillation.

Atmospheric Neutrinos   Super-Kamiokande has observed a zenith angle dependence that is consistent with flavor change of atmospheric muon neutrinos through oscillations with a baseline of the Earth's dameter. The zenith angle dependence for electron neutrinos is consistent with Monte Carlo calculations for no flavor change, implying that the muon flavor change is predominantly to tau neutrinos. The hypothesis of neutrino oscillations is consistent with measurements made by a number of other detectors of an anomalous ratio of muon to electron atmospheric neutrinos.

Solar Neutrinos   Since Davis' experiments starting in the 1960's, a discrepancy was identified between the experimental measurements and the theoretical calculations for solar neutrino fluxes. The fluxes are factors of two or three lower than predictions in each case, leading to the conclusion that either solar models are incomplete or there are processes occurring such as flavor change to other neutrino types for which the experiments have little or no sensitivity. This 30-year old discrepancy had come to be known as the "Solar Neutrino Problem".

Many attempts have been made to understand these discrepancies in terms of modifications to the solar model, without significant success. The results may be understood in terms of neutrino flavor change with matter enhancement in the sun. However, because the various experiments have different thresholds and are sensitive to different combinations of the nuclear reactions in the sun, this explanation is solar model-dependent. Solar model-independent approaches, including searches for spectral distortion, day-night and seasonal flux differences provided no clear indication of flavor change.

Measurements by the Sudbury Neutrino Observatory (SNO) of interactions of ^8B solar neutrinos in a heavy water detector have provided a solar-model-independent "appearance" measurement of neutrino flavor change by comparing charged current (CC) interactions on deuterium sensitive only to electron neutrinos and neutral current (NC) interactions sensitive to all neutrino types. A null hypothesis test for flavor change was performed, assuming no spectral change for the CC reaction. The flux of active neutrinos or anti-neutrinos other than electron neutrinos inferred from the NC measurements yielded a 5.3σ difference from the CC flux, providing clear evidence for flavor change. The result for the total active neutrino flux obtained with the NC reaction, $5.09^{+0.44}_{-0.43}(stat.)^{+0.46}_{-0.43}(syst.)$, is in very good agreement with the value calculated (Bahcall et al, 2001) by solar models: $5.05 \pm 1.0 \times 10^6$ cm^{-2}s^{-1}.

The solar neutrino measurements to date are best fit by neutrino oscillation parameters (see Table 1) including the MSW effect in the sun, referred to as the Large Mixing Angle (LMA) region. Note that the matter interaction defines m_2 to be greater than m_1 and that the mixing angle is somewhat smaller than maximal mixing.

Terrestrial Measurements   Measurements of the survival of ν_μ neutrinos produced at the KEK accelerator have been made with the Super-Kamiokande detector, (K2K experiment). The preliminary data (Nishikawa, 2002) show agreement with the m_2 to m_3 oscillation parameters observed for atmospheric neutrinos. The KamLAND experiment (Eguchi et al, 2003) has studied the flux of electron anti-neutrinos observed at a 1000 ton liquid scintillator detector (converted from the original water-based Kamiokande detector). They find a flux suppression consistent only with the LMA region for m_1 - m_2 oscillation as defined by solar neutrinos and restricting the region obtained with solar neutrino measurements alone. Results from the LSND experiment have indicated the appearance of a small flux of anti-ν_e from an anti-ν_μ accelerator beam. The majority of the allowed oscillation region for this experiment has been restricted by the Karmen experiment. The MINIBOONE experiment has just begun operation with neutrino beams from Fermilab and should approach the LSND measurements with substantially higher sensitivity.

Summary of flavor change information to date   Atmospheric, solar, and reactor neutrino oscillation data currently fix or limit the 3 angles. They also provide values for the differences between the squares of the masses. They provide no information yet on the phase(s). The data to date is summarized in Table 1.

2.3.   Neutrino Mass

The most sensitive direct measurements of electron neutrino mass have been made by searching for curvature induced near the end point of the spectrum of electrons emitted during the beta decay of tritium. The current limit obtained from these measurements is 2.8 eV (90 % CL.). Measurements of neutrinoless double beta decay are also sensitive to neutrino mass if the neutrino is a Majorana particle. Measurements to date set limits less than 0.4 eV for the effective mass associated with this process. There is also a controversial claim of a greater than 2 σ effect for a mass of 0.35 eV in a neutrinoless double beta decay measurement in Ge reported by a subset of the Heidelberg-Moscow experimental group.

Table 1.   Current knowledge of active neutrino mass and mixing from neutrino oscillations. One-σ errors are shown, except for θ_{13}, which is at the 90% CL.

Quantity	Value
θ_{12}	$32.6(32)^o$
θ_{13}	$< 10^o$
θ_{23}	$45(8)^o$
δ_{CP}	?
$m_2^2 - m_1^2$	$+7.3(11) \times 10^{-5}$ eV^2
$m_3^2 - m_2^2$	$\pm 2.5(6) \times 10^{-3}$ eV^2

Model-dependent limits with sensitivity of about 1 eV can also be obtained from combined fits to the cosmic microwave and large scale structure data.

3.   Future measurements

All of the types of measurements discussed above are being pursued very actively for the future. The next generation measurements for tritium beta decay and neutrinoless double beta decay should extend the mass sensitivity by a factor of about 10. This sensitivity is approaching the mass differences identified by the oscillation measurements. Flavor change measurements will be extended for solar and terrestrial neutrinos with improved accuracy. The definition of these parameters has also led to plans for a next generation of long-baseline experiments to quantify θ_{13} through accelerator and reactor experiments and seek the mass hierarchy through matter interactions and CP violating phase through experiments with accelerator and detector properties scaled up by factors of 10.

Our knowledge of neutrino properties has expanded greatly during the past 10 years. The next generations of experiments have the potential to provie as comprehensive information for the lepton sector as has been obtained for quarks, thereby making it possible to use neutrinos as a unique astrophysical probe.

References

Please note that, in the interests of space, all experimental references contained in the 2002 summary by the Particle Data Group are not repeated here.

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